Available online at www.sciencedirect.com

SCIENCE DIRECT®

Marine Pollution Bulletin 51 (2005) 459–469

MARINE POLLUTION BULLETIN

www.elsevier.com/locate/marpolbul

Mapping water quality and substrate cover in optically complex coastal and reef waters: an integrated approach

S.R. Phinn [a,b,*], A.G. Dekker [a,c], V.E. Brando [a,c], C.M. Roelfsema [a,b,d]

[a] *Cooperative Research Centre for Coastal Zone, Estuary and Waterways Management, Brisbane, Queensland 4069, Australia*
[b] *Biophysical Remote Sensing Group, School of Geography, Planning and Architecture, University of Queensland, Brisbane, Queensland 4072, Australia*
[c] *Environmental Remote Sensing Group, CSIRO Division of Land and Water, Canberra, A.C.T., 2601, Australia*
[d] *Centre for Marine Studies, University of Queensland, Brisbane, Queensland 4072, Australia*

Abstract

Sustainable management of coastal and coral reef environments requires regular collection of accurate information on recognized ecosystem health indicators. Satellite image data and derived maps of water column and substrate biophysical properties provide an opportunity to develop baseline mapping and monitoring programs for coastal and coral reef ecosystem health indicators. A significant challenge for satellite image data in coastal and coral reef water bodies is the mixture of both clear and turbid waters. A new approach is presented in this paper to enable production of water quality and substrate cover type maps, linked to a field based coastal ecosystem health indicator monitoring program, for use in turbid to clear coastal and coral reef waters. An optimized optical domain method was applied to map selected water quality (Secchi depth, Kd PAR, tripton, CDOM) and substrate cover type (seagrass, algae, sand) parameters. The approach is demonstrated using commercially available Landsat 7 Enhanced Thematic Mapper image data over a coastal embayment exhibiting the range of substrate cover types and water quality conditions commonly found in sub-tropical and tropical coastal environments. Spatially extensive and quantitative maps of selected water quality and substrate cover parameters were produced for the study site. These map products were refined by interactions with management agencies to suit the information requirements of their monitoring and management programs.

Keywords: Remote-sensing; Coastal; Coral reef; Seagrass; Substrate; Water quality; Mapping and monitoring

1. Introduction-monitoring and managing coastal and reef environments

1.1. Overview

Resource management activities for conservation or sustainable use rely on several critical components: (1) accurate and up-to date information on the components and processes making up the environment; (2) an understanding of "how" the environment and its components function; and (3) an ability to monitor the environment's components and processes. These components translate to a need for spatial information in the form of baseline mapping and inventory, monitoring programs, and predictive models (Phinn et al., 2002; Phinn et al., 2003; Trinder and Milne, 2003). Collection of information for resource mapping and monitoring has focused on direct (field survey) and indirect (remote sensing) sampling techniques to produce maps of environmental parameters considered representative of environmental health or condition. Key parameters are labeled as ecological or environmental indicators, and extensive work has been conducted in coastal environments, from local to global scales, on monitoring and management programs

* Corresponding author. Address: Biophysical Remote Sensing Group, School of Geography, Planning and Architecture, University of Queensland, Brisbane, Queensland 4072, Australia. Tel.: +61 7 33656526; fax: +61 7 33656899.
E-mail address: s.phinn@uq.edu.au (S.R. Phinn).

0025-326X/$ - see front matter
doi:10.1016/j.marpolbul.2004.10.031

based on selected indicators (Edwards, 1998; Belfiore, 2003; Rice, 2003). The application of indicators in coral reef environments has not progressed to the same level (Chin, 2003). A critical component in any monitoring program is an accurate, precise, reliable, repeatable and cost effective method for mapping environmental indicators. This paper presents a novel approach that integrates remote sensing and field methods for mapping and monitoring recognized indicators of coastal and coral reef ecosystem condition.

1.2. Background literature

Remote sensing applications in coastal and coral reef environs have developed over the past 30 years to map characteristics of aquatic environments, from the water surface, to water column constituents and substrate cover types (Edwards, 1999; Green et al., 2000; Dekker et al., 2001; Coppin et al., 2004; Hochberg and Atkinson, 2003; Malthus and Mumby, 2003; Mumby et al., 2004). Examples include operational mapping and monitoring programs for assessing oceanic productivity, based on the measurement of ocean colour through mapping concentration of organic constituents in the water column (Mobley, 1994; Gordon, 1995; Carder et al., 1999; IOCCG, 2000). Mapping the concentration of organic and inorganic materials has been implemented extensively in lake and riverine water bodies (Lindell et al., 1999; Dekker et al., 2001). Mapping of substrate cover types and their biophysical properties has been carried out successfully in optically clear, shallow (<20 m) coastal and reef waters. With limited exceptions (Lee et al., 1998; Lee et al., 1999), successful passive remote sensing applications have mapped either water column constituents or substrate cover types, but not both. However, both water quality and substrate characteristics are recognized as indicators of coastal and coral reef condition.

1.3. Scope of proposed approach

Production of accurate and reliable maps of water-quality or substrate types in coastal waters is complicated by varying optical properties and concentrations in the water column. Coastal embayments such as Moreton Bay are highly dynamic and display optically complex features, due to oceanic tidal influences and terrestrial inputs from rivers and creeks (McEwan et al., 1998; Tibbets et al., 1998). Case 1, or oceanic waters have optical properties dominated by phytoplankton and associated pigments. Case 2 waters, typically coastal and lacustrine waters, contain constituents that do not co-vary with chlorophyll, such as coloured dissolved organic material (CDOM), total suspended sediments (TSM)/inanimate detritus (tripton) and bacteria (Gordon and Morel, 1983; Lindell et al., 1999). Remote sensing techniques have been successfully applied for operational mapping of the biophysical properties of case 1 waters (IOCCG, 2000). However, Case 2 waters continue to represent a challenge to remote sensing techniques, and recent reviews on the state of the art in this area highlight the need for new approaches to these optically complex waters (IOCCG, 2000; Dekker et al., 2001; Malthus and Mumby, 2003).

1.4. Methodology—optimised optical domain approach

We integrated two methods that can be used with commercially available satellite image data. The first method maps concentrations of the constituents (chlorophyll, coloured organic matter and tripton) controlling the optical properties of a water body (Phinn et al., 2004). The second method maps the substrate cover type and its characteristics (Roelfsema et al., 2001; Phinn et al., 2004). The products of these two methods are then integrated into a single map, showing both water quality and substrate cover information. This approach is described using Moreton Bay (Fig. 1), south-eastern Queensland, as a representative example of the range of water quality and substrate cover types typically found in coastal and coral reef environments. This approach divides an image of a coastal or reef environment into segments based on the transparency of the water column, substrate visibility and the source of the optically active substances.

2. Example application: mapping water quality and substrate in Moreton Bay, Queensland, Australia

2.1. Monitoring requirements—indicators for water quality and seagrass condition

Moreton Bay was selected as the demonstration project for two reasons: (i) the range of substrate types and water column characteristics represent those typically found in other sub-tropical and tropical coastal and reef environs; and (ii) it has an established "coastal ecosystem health" monitoring and management program using recognised ecological indicators related to substrate and water quality (EHMP, 2004). Moreton Bay substrate contains significant areas of unconsolidated sediments, ranging from fine-silt muds in the western ay to silicate sands in the eastern Bay. Extensive seagrass beds and macroalgae occur throughout the bay, as do bedrock outcrops and fringing reefs. Due to the number of creeks and rivers that drain into the western part of the Bay and the oceanic openings on its eastern side, the water column usually ranges from freshwater dominated, and often turbid in the western Bay, to oceanic water dominated and clear blue-green waters of the eastern Bay.

Fig. 1. Landsat 7 ETM+ image enhanced true-colour scene of Moreton Bay, captured at 0945 on March 21, 2002 and overlaid with bathymetric contours.

The Ecological Health and Monitoring Program (EHMP) was established as a result of a scientific taskforce examining controls on Moreton Bay's water quality and providing recommendations to the local governments with catchments draining into the Bay on how to best manage and improve water quality (Dennison and Abal, 1999). The EHMP provides an annual assessment of the condition of Moreton Bay and the creeks and rivers draining into it, as a report card and scientific report (EHMP, 2004). Under the EHMP selected environmental indicators are regularly monitored through an extensive point-sampling field program. Parameters measured in Moreton Bay include: Secchi depth; turbidity (in NTU); chlorophyll concentration; temperature; dissolved oxygen concentration; photosynthetically active radiation (PAR); the depth range of seagrasses; and stable isotope analysis to estimate sewage concentration. Point data are interpolated using a Kriging algorithm to provide maps showing spatial variation in the ecosystem health parameters over Moreton Bay. A number of the EHMP parameters, e.g. chlorophyll concentration, turbidity, Secchi depth, PAR and substrate types, have been successfully mapped using remote sensing. A natural progression would be to determine if commercially available remotely sensed data could be used to map these parameters with sufficient accuracy to contribute to the monitoring program.

2.2. Optimised optical domain approach for mapping optically complex waters

If coastal and coral reef environments are to be monitored on a regular basis using the current and next generation of earth resource monitoring satellites, a mapping approach capable of working in both Case 1 and Case 2 waters is essential. As shown in the Landsat 7 Enhanced Thematic Mapper (ETM) image taken at low-tide (Fig. 1), Moreton Bay is a complex coastal embayment with a mix of Case 1 and Case 2 waters, similar to conditions found along the coastal edge of the Great Barrier Reef Lagoon. Case 1 waters dominate in the optically deep tidal inflow areas in the north-east and eastern sections of the bay. Similar clear water bodies occur over areas where substrate is visible in these areas, however these are considered as Case 2 waters. Inputs from the Caboulture, Pine, Brisbane, Logan and Albert Rivers, and numerous small creeks provide sediment and organic material for the western part of the bay. Previous approaches to mapping water quality parameters have applied empirical regression-based techniques reliant on assumptions that the bay was dominated by Case 1 waters (Gabric et al., 1998; Islam et al., 2002; Islam et al., 2003; Islam et al., 2004). Mapping results from these studies suffered limitations because Case 2 waters confound the results. The mapped water quality parameters (chlorophyll and total suspended sediment concentrations), are distorted where the substrate is visible in shallow clear waters. As a result, variations in mapped parameters are due to the influence of substrate features, not water column or surface features.

Through a process of trial and elimination drawing on experience from several coastal and coral reef environments we developed a sequence of image processing techniques for application to satellite or airborne images of the coastal zone to produce maps depicting absolute concentrations of organic and inorganic material in the water column. Concentrations of these materials are internationally recognised measurements of water quality in coastal, reef, estuarine and riverine areas (IOCCG, 2000). In addition, the process enables production of maps depicting the spatial distribution of substrate cover types (e.g. sand, seagrass, coral, algae etc.) and in some cases maps of biophysical properties of the substrate cover type (e.g. seagrass density). Fig. 2 provides an overview of the sequence we have referred to as an "optical domain based mapping of aquatic coastal ecosystem properties" approach.

2.3. Underwater light climate development

The first stage in developing an image processing approach capable of working in both turbid and clear waters was to characterise the optical properties of the water bodies typically found in Moreton Bay. The second stage was to develop mapping algorithms capable of using these parameters (Brando and Dekker, 2003). The underwater light-climate model describes how light is absorbed and scattered by components of the water column. Specific inherent optical properties or SIOPs are material properties of the water column which are independent of the incident light field. AOPs (apparent optical properties) are dependent on the incident light field. Measurements of the spatial variability of SIOPs indicates the how the rivers and ocean waters interact in the bay. Estimation of SIOPs was a major activity during the field sampling programs carried out in Moreton Bay in February 2001 and March 2002. Full details of the sampling protocols used to collect these parameters are described in Brando and Dekker (2003) and Phinn et al. (2004).

Representation of the underwater light climate at 11 locations throughout Moreton Bay was provided by the measurement of two inherent optical properties (IOP) and two apparent optical properties (AOP). The IOP's were spectra of absorption and backscattering; and the two apparent optical properties were spectra of vertical attenuation and subsurface irradiance reflectance R(0-). These quantities represent key components of hydrologic radiative transfer equations (Dekker et al., 2001) that quantify how much sun and sky light is absorbed and scattered, and transmitted to an imaging sensor, when light interacts within a water body containing organic and inorganic material. Hence, the underwater light climate plots provide a quantitative definition for each location in the Bay of how much incident light is absorbed and scattered, how much light is attenuated and reflected, and what proportion of these interactions are due to the various organic and inorganic constituents of the water column.

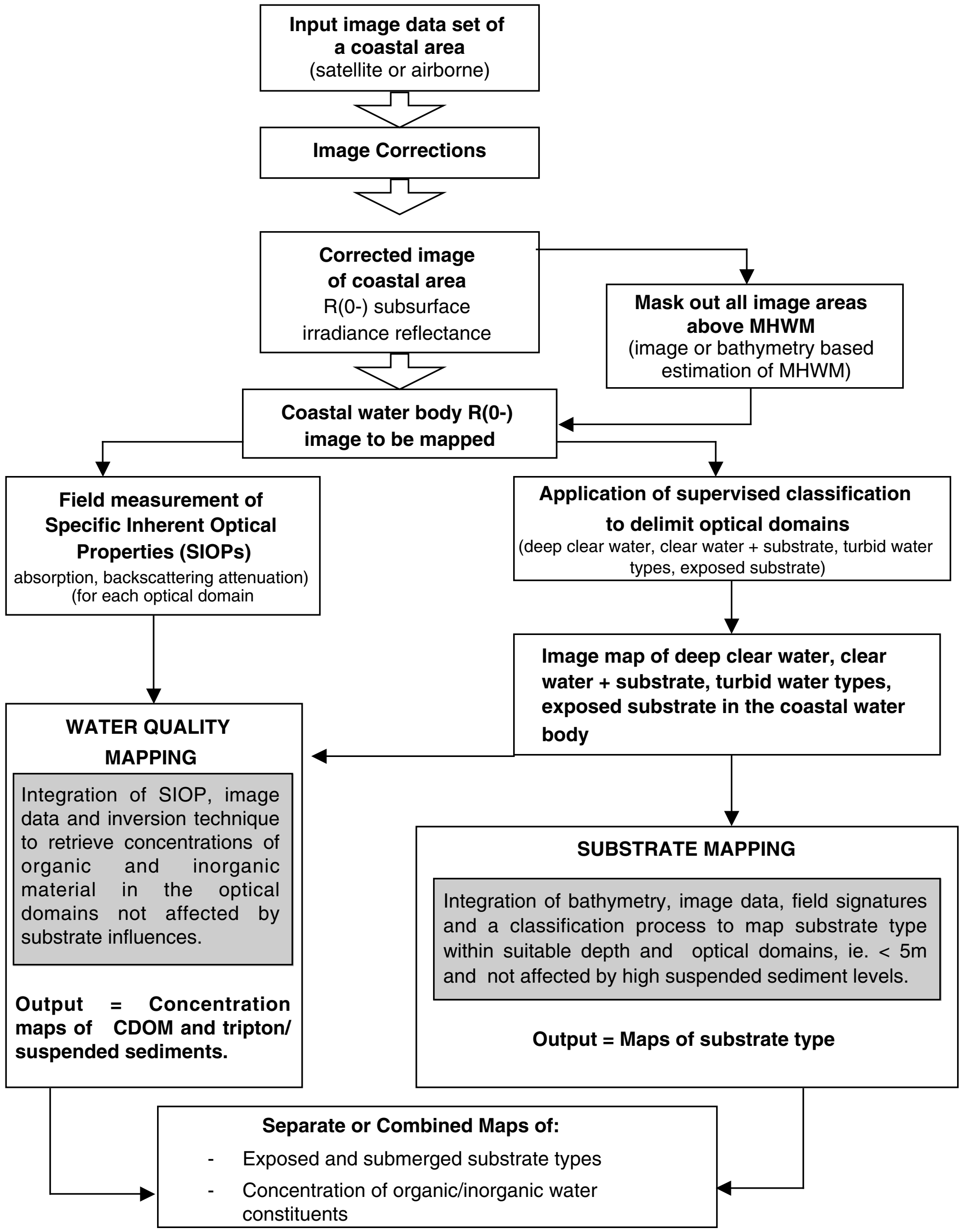

Fig. 2. Flowchart of optimized optical domain processing approach.

The following parameters are graphed (Fig. 3) to present the underwater light climate at field sample sites, and a full set of parameters for Moreton Bay are presented in Phinn et al., 2004):

- The tidal stage at which samples and measurements were taken.
- Spectral absorption by phytoplankton, tripton, water and CDOM.

This graph indicates which constituents of water column are absorbing specific wavelengths of light. Water that is phytoplankton rich will absorb highly in blue and red, and not as much in green, hence its green colour.

- Spectral backscattering by water, phytoplankton and tripton.

This graph indicates which constituents are scattering the most incident light back to the sensor. Water bodies with large suspended sediment load will have high tripton concentrations and reflect more strongly in all wavelengths due to particulate scattering. Clear water bodies scatter predominantly blue light, due to molecular level scattering, hence their blue colour.

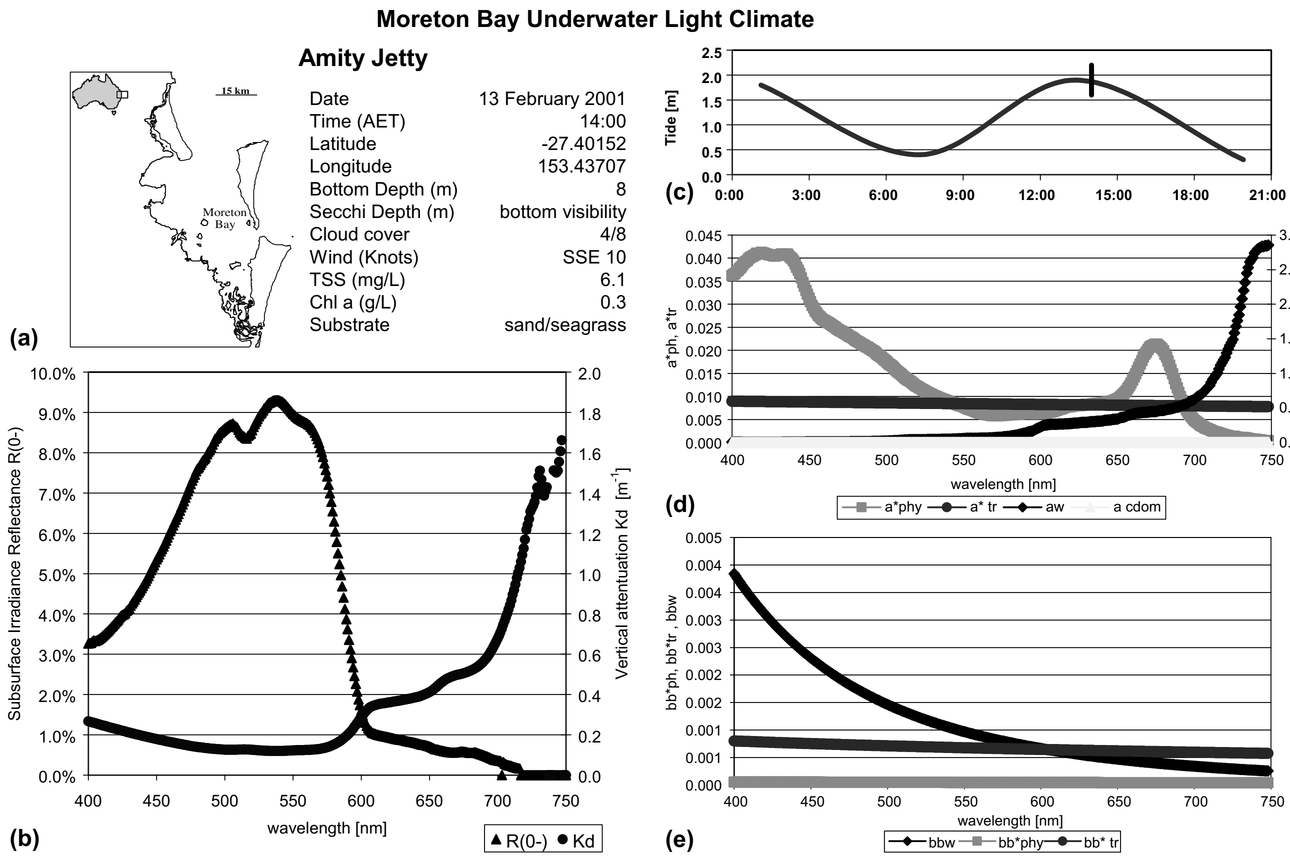

Fig. 3. Example plot showing underwater light climate parameters as measured from field sampling program in Moreton Bay, February 2001 and March 2002.

- Spectral subsurface irradiance reflectance and the vertical attenuation coefficient.

In this plot the reflectance curve defines the "colour" of sunlight reflected from the sample site and vertical attenuation curve shows the spectral distribution of light attenuation with depth in the water column takes place.

- Environmental conditions at the time of underwater light climate measurements.

The SIOPs of the 11 sites s exhibit a grouping corresponding to the different coloured regions of Moreton Bay as follows:

(i) Case 1 oceanic waters, corresponding to the Amity Jetty site, with absorption dominated by phytoplankton and water and backscatter dominated by water (these can be sub-divided into optically deep regions and those with visible substrate).
(ii) A complex of green-brown waters (Case 2), corresponding to North Peel, Shipping Channel, Deception Bay and Coffee Pot sites, with absorption dominated by phytoplankton, tripton and water and backscatter dominated by tripton and water.
(iii) Complex near coastal areas with both turbid and clear Case 2 conditions in Deception Bay at Godwin Beach, with absorption dominated by phytoplankton, tripton and CDOM.
(iv) Turbid, Case 2 river waters in the Brisbane River at Luggage Point, Colmslie boat ramp and in the Logan River, with absorption dominated by tripton, CDOM and phytoplankton and backscatter dominated by tripton.
(v) Tidal channels with predominantly clear waters in Pumicestone Passage and the Southern Bay islands to Jumpinpin Bar (not sampled for SIOPs).

These optical parameterizations will be used as input for the retrieval of the optically active constituents from the fully corrected Landsat 7 ETM imagery.

2.4. Mapping water quality

We used an analytical model of underwater light-climate applicable to commercially available Landsat 7 ETM image data, to retrieve concentrations of tripton (as a surrogate for total suspended matter), colored dissolved organic matter (CDOM), Secchi depth, and K_d (PAR) (the diffuse attenuation coefficient integrated over PAR). This model is a simplification of the full radiative transfer equations used to quantify the interactions of sunlight with waterbodies (Dekker et al., 2001). Phinn et al. (2004) explains the derivation of this method as a "translation" to multispectral imagery of the approach developed by Brando and Dekker (2003) for retrieving concentrations of chlorophyll, CDOM and tripton in coastal waters using three spectral bands from a spaceborne hyperspectral R(0-) image.

Sensitivity analyses in earlier work demonstrated that it was not possible to retrieve chlorophyll at the concentration levels present in Moreton Bay given the noise levels of Landsat 7 ETM imagery (Phinn et al., 2004). Thus, this project focused on retrieving the concentrations of Tripton (as a surrogate for total suspended matter) and CDOM from the three spectral bands in the visible range of Landsat 7 ETM imagery. We extracted subsurface irradiance reflectance R(0-) using the program, "c-WOMBAT-c" which corrects for atmospheric attenuation and air-water interface effects (Brando and Dekker, 2003; Phinn et al., 2004).

Concentration(s) of the optically active constituents were retrieved from corrected Landsat 7 ETM image data using an optimisation technique that selected the most appropriate SIOPs as an optical parameterization for each pixel of the image (Fig. 4). The optimization was implemented by iteratively applying a singular value decomposition inversion algorithm to match each Landsat image pixel over Moreton Bay to one of the SIOP sets measured from the February 2001 intensive field campaign (Fig. 3). A second model was then applied, using the SIOPs and pixel R(0-) values, to estimate the concentration of tripton and CDOM for each pixel (Phinn et al., 2004).

By using this combination of models the estimated output concentrations and SIOPs can also be used in an inverse approach to estimate the R(0-) values for each pixel. Comparison of the estimated R(0-) values with input R(0-) provides a measure of how well the model estimated concentrations of tripton and CDOM in each pixel. This quantity can also be interpreted as a measure of the optical closure in each pixel or a "level of confidence" of water quality parameter estimates. If this value exceeds a set threshold, the pixel can be flagged and "not mapped". Otherwise, the concentration values associated with the best optical closure are used for the maps of the primary products (i.e. CDOM and tripton), while the measure of the optical closure and the optical parameterization selected for each pixel are used as quality control products.

Once the concentrations of the CDOM and Tripton are known, as well as the optical parameterization of each pixel, water transparency can be mapped from

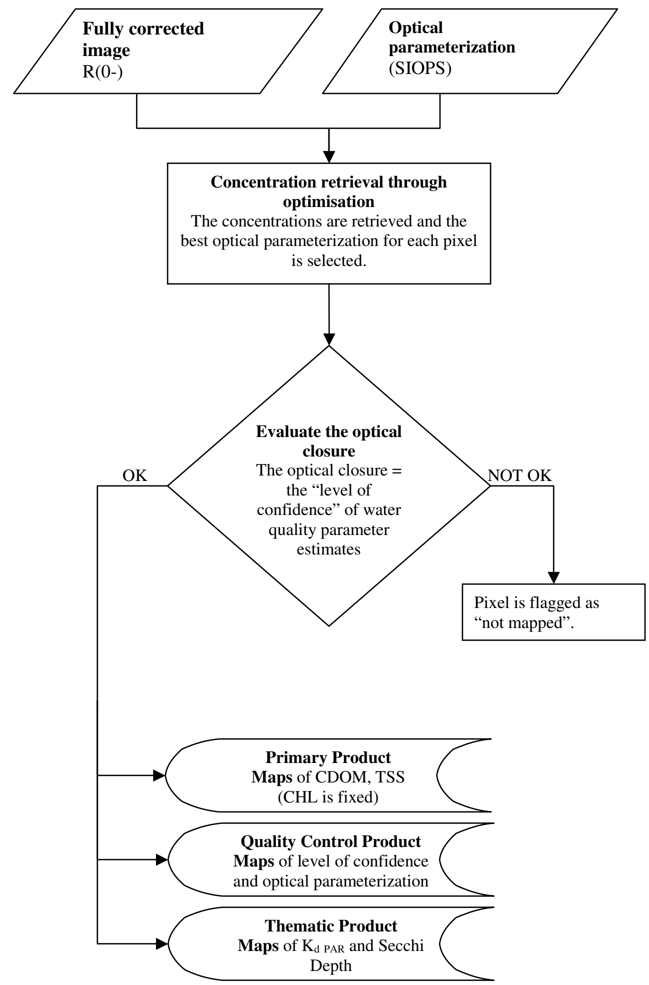

Fig. 4. Outline of the steps used in the bio-optical model to estimate concentrations of water column constituents from the Landsat 7 ETM image data.

the Landsat 7 ETM image. The method for mapping Secchi depth and Kd(PAR) maps is also based on an analytical model of the underwater light-climate (Phinn et al., 2004). Fig. 5 depicts Secchi depths retrieved from the Landsat 7 ETM data of Moreton Bay of the 21 March 2002 in comparison with the interpolated Secchi depth map produced by applying Kriging algorithm to EHMP point samples collected between 11 and 18 March 2002. Inshore areas and river mouths are associated with consistently low Secchi depth estimates in the image. This is broadly consistent with field sampled data and with expectations of physical processes such as: tidal and wind driven re-suspension in shallow embayments; river discharges; and re-suspension from very shallow banks.

An evaluation of the accuracy of the image based approach is presented in Fig. 5c, showing a scatterplot of the Secchi depth values retrieved from the 14 February 2001 Landsat ETM image versus the same parameter measured in situ by EHMP over the bay from February

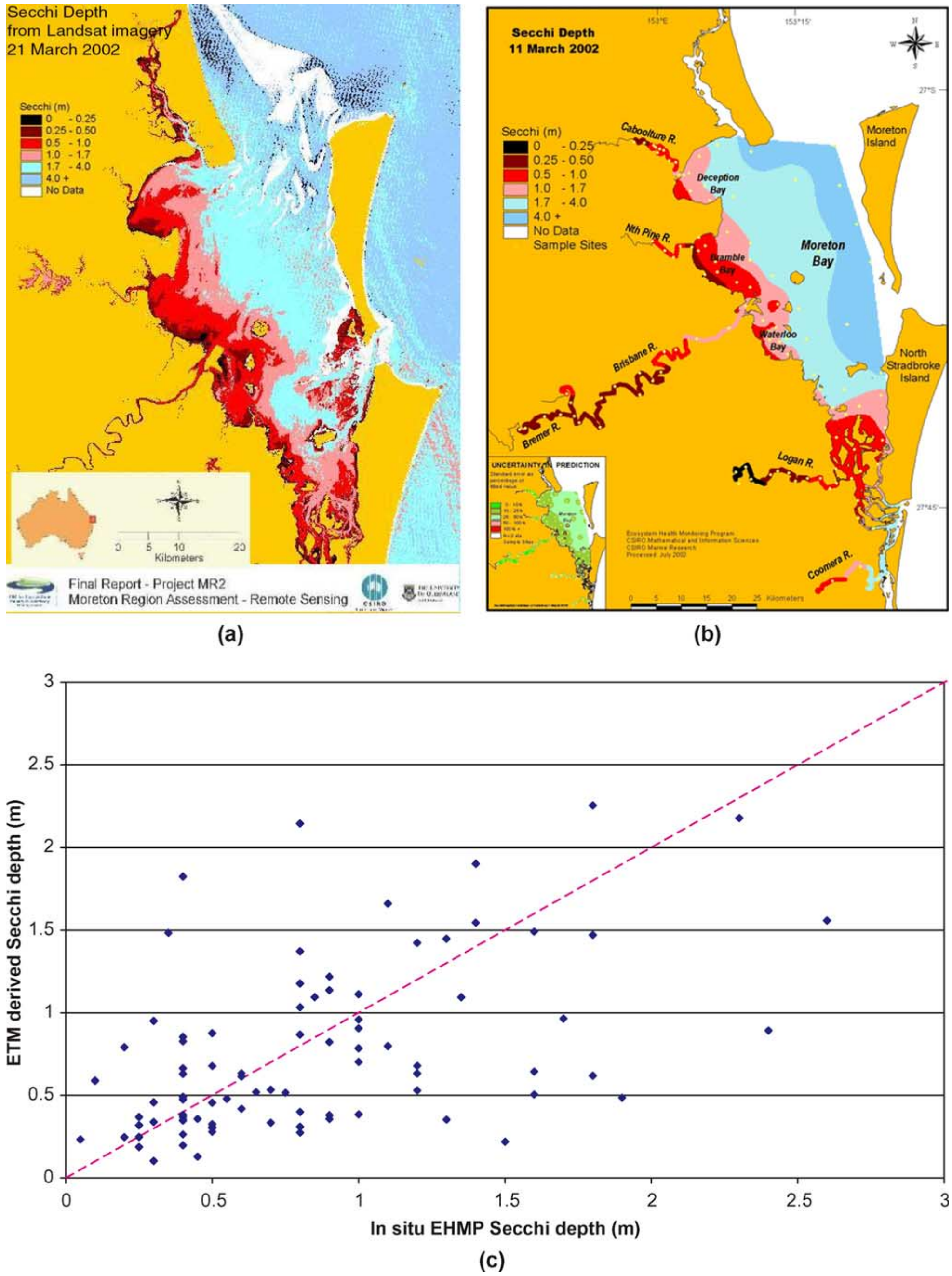

Fig. 5. Secchi depth estimates for Moreton Bay for March 2002. (a) Secchi depth estimated from Landsat 7 ETM image captured on 22 March 2002. (b) Interpolated map of Secchi depth from field sampling sites (yellow dots) of the Ecological Health and Monitoring Program collected on March 11–18 2002. (c) Scatterplot of the Secchi depth values retrieved from the 14 February 2001 Landsat ETM image versus the same parameter measured in situ by EHMP over the bay from February 5 to 26, 2001.

5 to 26, 2001. There is a significant level agreement between the data sets, indicated by the correlation ($r = 0.6$) of the Secchi depth retrieved from the imagery versus the in situ data.

Some of the differences between the Secchi depth maps may be explained by time differences between image acquisition and field sampling of Secchi depths, and the method used to interpolate the field measured data. The time lag between the in situ measurements that were used only for the EHMP map and the image acquisition ranged from three to 10 days. Interpolation of the point based EHMP field samples of Secchi depth assumes a linear gradient and may not detect discontinuities associated with tidal eddies and resuspension of sediments due to trawling in south-western Deception Bay and east of Redcliffe. Observed variations in tidal levels, rainfall and river discharge in the month prior to the March 21 2002 image indicated that Moreton

Bay received minimal freshwater or riverine discharges, in addition no rainfall events were recorded in the Moreton Bay catchment between the dates of in situ measurements and the Landsat 7 ETM image acquisition. However, the most obvious difference between the maps is the increased and complete spatial detail of the satellite image based map, compared to the necessarily smooth interpolated map.

2.5. Mapping substrate cover type characteristics

The goal of this portion of the mapping program was to produce a map of inter- and sub-tidal substrate cover types (seagrass, macroalgae etc.) in water bodies where substrate was visible. A fully corrected and land-masked Landsat 7 ETM image was subject to further masking to exclude those regions of Moreton Bay where the water column was too turbid or deep to enable reliable mapping of substrate cover types. Three image analysis approaches were combined to map: (i) submerged substrate types; (ii) submerged substrate types in green waters; and (iii) exposed intertidal substrate types from the 21st March 2002 Landsat ETM image. Details of these methods are provided in (Phinn et al., 2004; Roelfsema et al., 2001). This mapping was conducted in areas that were not dominated by turbid waters (high total suspended matter or tripton levels), i.e. where the substrate was visible. Optical domains corresponding to clear water with substrate, and the exposed substrate, were extracted for further analysis. In the former case, a simple unsupervised classification, combined with field data and knowledge was used to map the location of seagrass zones, and a harmful algal bloom (*Lyngbya majuscula*) and to estimate the density of their horizontal coverage. Depth range was also restricted to ensure that deep seagrass beds were not confused with shallow dense beds. Additional classification routines were developed to map submerged substrate in the greener waters of northern Deception Bay, and exposed substrates on the western portion of the Bay from Godwin Beach to the mouth of the Logan River. Figs. 6 and 7 demonstrate the map of exposed substrate, seagrass and *Lyngbya majuscula* distribution.

2.6. Integrated water quality and substrate maps

Although the individual maps of substrate and water quality are useful for science and management applications on coastal and coral reef environments, refinements to the algorithms and further analysis of the image based maps would provide information better suited to monitoring requirements. Research is currently underway on semi-analytic models to simultaneously extract water column optical properties (water quality parameters) and to map substrate type and depth, in areas where substrate is visible. Hyperspectral image data or multi-temporal data, may be necessary to realise this (Phinn et al., 2004).

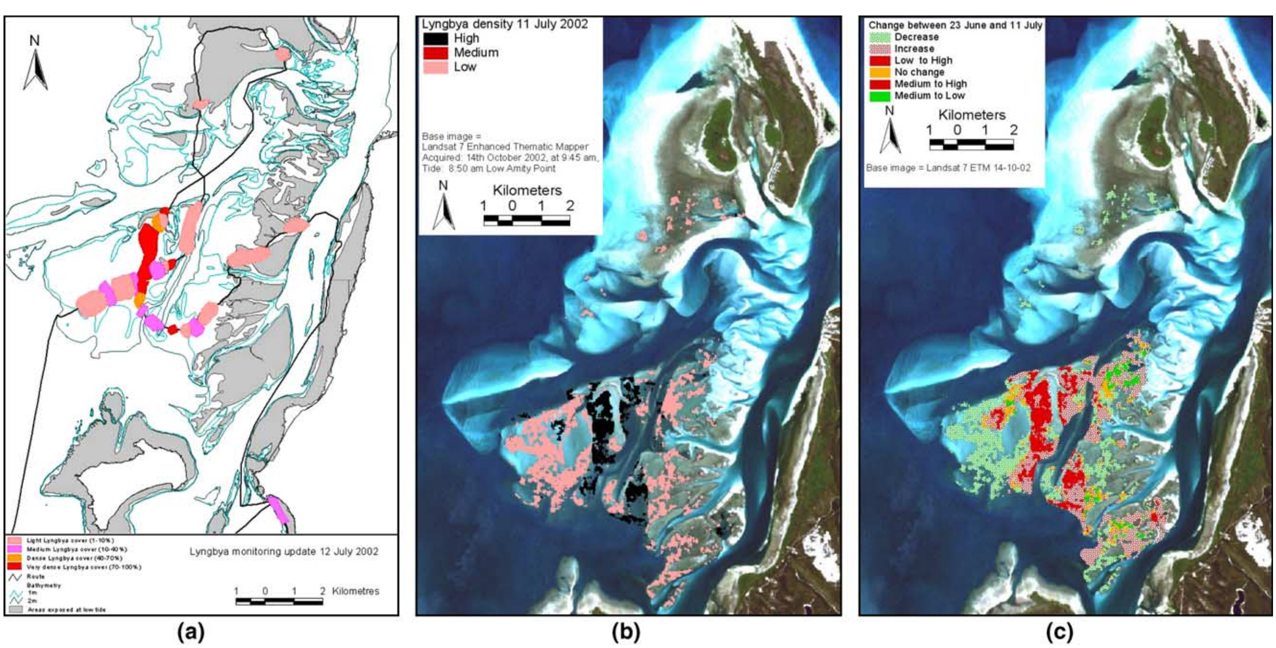

Fig. 6. *L. majuscula* distribution maps for the Eastern Banks section of Moreton Bay. (a) Field survey map produced by Queensland Parks and Wildlife Service Rangers for July 12, 2002. Dark line is a GPS record of survey boat track and colours represent algal bloom cover. (b) *L. majuscula* distribution map produced from supervised classification of a Landsat 7 ETM scene captured on 11 July 2002. (c) Change in *L. majuscula* cover between 11 July 2002 and 23 June 2002 based on post-classification comparison of separate *L. majuscula* distribution maps and corresponding Queensland Parks and Wildlife surveys for 2002.

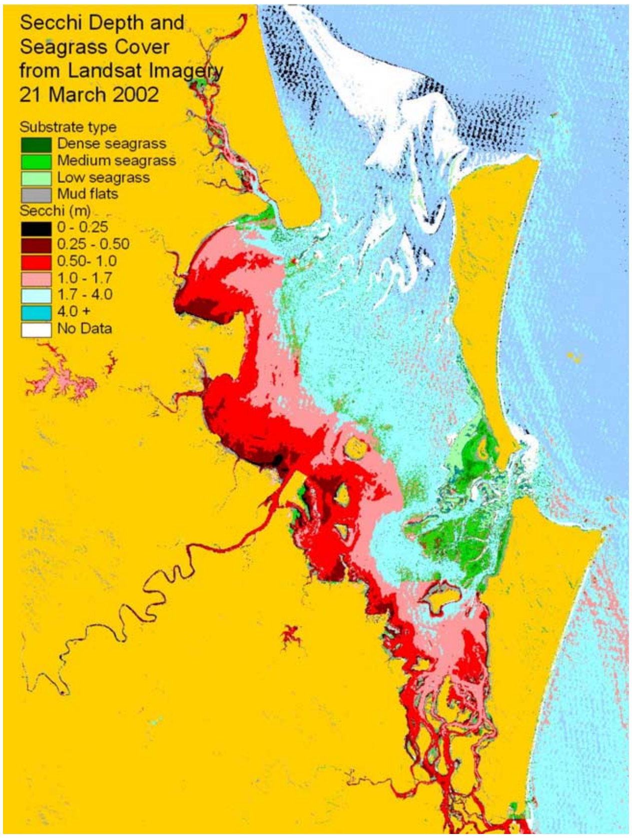

Fig. 7. Integrated product map for Moreton Bay derived from Landsat 7 ETM image data captured on 21 March 2002. The map shows substrate cover types in exposed (intertidal) areas and in areas where the substrate was visible. The substrate cover map is overlaid on map showing estimated Secchi depth.

3. The future: operational mapping of coastal and reef ecosystem health indicators in optically complex environments

Commercially available, moderate spatial resolution, multi-spectral satellite image data sets can be used in conjunction with field observations to produce maps of biophysical properties for coastal and coral reef environments suited to baseline mapping and monitoring of recognized ecosystem health indicators. The demonstration project outlined in this paper illustrated the need to overcome two challenges: (1) development of mapping approaches that work across the range of water-clarity found in coastal and coral reef environments; and (2) integrating the remote sensing products with field-measurement of ecological indicators as part of an ongoing monitoring program. Success in these approaches requires interaction with field-based ecosystem health monitoring activities for both validation of the image-based products and delivery of integrated field and image based products. The latter point is essential, as non-remote sensing scientists and managers need to be able to directly evaluate a product from their existing field sampling (e.g. Secchi depth) with the same parameter derived from a satellite image. Once the correspondence between the two products is understood, both field and image based methods can be used to their full extent. Typically, field surveys provide accurate and precise measurements at a limited number of key sites, while image data provide extensive spatial coverage of the study area but slightly lower accuracy.

The availability of commercial and internet-served satellite image data and image based map products for biophysical variables is continuing to improve, coupled with improved access to image processing and GIS software packages. Resource monitoring and management agencies are therefore at a stage where a range of continually updated image data sets and derived products can be obtained and integrated in mapping and monitoring programs. To ensure effective use of the data, especially in coastal and coral reef environments, a complete mapping approach similar to the one outlined here could be adopted. Whatever suite of image-based products are finally chosen, for operational cost-effective remote sensing data based mapping, it is essential to create an integrated processing chain. This project established the basis for such a processing chain. Application of the processing chain to an image data set converts it to a format where it can be directly compared to previous images of the same area and used to derive calibrated maps of biophysical variables, e.g. supra/inter/sub-tidal products.

Future applications of remote sensing for monitoring set ecosystem health indicators in coastal and coral reef environments, may need to address the following questions:

- Can remotely sensed data add to, enhance or replace existing methods for measuring the marine environment?
- Is remote sensing based cost-effective or can it can it be made cost-effective? As an example, current processing costs for one Landsat scene for Moreton Bay for water quality would cost about 8 hours plus AUD$1200 for remote sensing image acquisition (provided all thematic data is available). Is this competitive with sending out boats and field teams and performing laboratory analyses to reach a similar level of information?
- Is higher spatial resolution image data (pixels <10 m × 10 m) useful for coastal monitoring and management?

Acknowledgments

Funding for this work was provided by grants from: (1) the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management to Dr's Dekker, Brando and Phinn and Mr Roelfsema; and (2) Lyngbya Scientific Taskforce/Moreton Bay Waterways Catchment Partnership, to Dr Phinn and Mr Roelfsema. Infrastructure, computing resources and technical support provided by Biophysical Remote Sensing and Marine Botany Groups (The University of Queensland) and Environmental Remote Sensing Group (CSIRO). The two anonymous reviewers and editor who provided useful suggestions to finish off the manuscript.

References

Belfiore, S., 2003. The growth of integrated coastal management and the role of indicators in integrated coastal management: introduction to the special issue. Ocean and Coastal Management 46 (3–4), 225–234.

Brando, V.E., Dekker, A.G., 2003. Satellite hyperspectral remote sensing for estimating estuarine and coastal water quality. IEEE Transactions on Geoscience and Remote Sensing 41 (6), 1378–1387.

Carder, K.L., Chen, F.R., Lee, Z.P., Hawes, S.K., Kamykowski, D., 1999. Semianalytic moderate-resolution imaging spectrometer algorithms for chlorophyll a and absorption with bio-optical domains based on nitrate-depletion temperatures. Journal of Geophysical Research 104 (C3), 5403–5421.

Chin, A., 2003. State of the great barrier reef. Great Barrier Reef Marine Park Authority, Townsville.

Coppin, P., Jonckheere, I., Nackaerts, K., Muys, B., Lambin, E., 2004. Digital change detection methods in ecosystem monitoring: a review. International Journal of Remote Sensing 25 (9), 1565–1596.

Dekker, A.G., Brando, V.E., Anstee, J.M., Pinnel, N., Kutser, T., Hoogenboom, E.J., Peters, S., Pasterkamp, R., Vos, R., Olbert, C., Malthus, T.J.M., 2001. Imaging spectrometry of water. In: de Jong, S.M. (Ed.), Imaging Spectrometry: Remote sensing and digital image processing. vol. 4, Kluwer Publishers, pp. 307–359.

Dennison, W.C., Abal, E.G., 1999. Moreton bay study: a scientific basis for the healthy waterways program. South East Queensland Water Quality Management Strategy/Brisbane City Council, Brisbane.

Edwards, A.J., 1999. Applications of satellite and airborne image data to coastal management. Coastal Regions and Small Islands Papers, Paris, UNESCO.

Edwards, D., 1998. Issues and themes for natural resources trend and change detection. Ecological Applications 8 (2), 323–325.

EHMP 2004. Ecosystem Health and Monitoring program 2002-2003. Annual technical Report. Brisbane, Moreton Bay Waterways and Catchment Partnership, 164 pp.

Gabric, A., McEwan, J., Bell, P.R.F., 1998. Water quality and phytoplankton dynamics in moreton bay, south-eastern queensland. I. Field survey and satellite data. Marine & Freshwater Research 49, 215–225.

Gordon, H., Morel, A., 1983. Remote assessment of ocean colour for interpretation of satellite visible imagery. A review. Springer, New York.

Gordon, H.R., 1995. Remote sensing of ocean color: a methodology for dealing with broad spectral bands and significant out-of-band response. Applied Optics 34 (36), 8363–8374.

Green, E.P., Mumby, P.J., Edwards, A.J., Clark, C.D., 2000. Remote sensing handbook for tropical coastal management. UNESCO, Paris.

Hochberg, E.J., Atkinson, M.J., 2003. Capabilities of remote sensors to classify coral, algae, and sand as pure and mixed spectra. Remote Sensing of Environment 85 (2), 174–189.

IOCCG 2000. Remote sensing of ocean colour in coastal and other optically complex waters. In: Sathyendrannath, S. (Ed.), Reports of the International Ocean Colour Coordinating Group. No. 3, IOCCG, Dartmouth, Canada, 140 pp.

Islam, Md.A., Gao, J., Ahmad, W., Neil, D., Bell, P., 2002. Quantification of chlorophyll concentration by means of multitemporal remote sensing in shallow coastal waters: challenges and feasibility. In: Proceedings of the 11th Australasian Remote Sensing and Photogrammetry Conference. Brisbane, 2–6 September, CD-Rom, Causal Publications, pp. 287–295.

Islam, Md.A., Gao, J., Ahmad, W., Neil, D., Bell, P., 2003. Image calibration to like-values in mapping shallow water quality from multitemporal data. Photogrammetric Engineering and Remote Sensing 69 (5), 567–575.

Islam, Md.A., Gao, J., Ahmad, W., Neil, D., Bell, P., 2004. A composite DOP approach to excluding bottom reflectance in mapping water parameters of shallow coastal zones from TM imagery. Remote Sensing of Environment 92 (1), 40–51.

Lee, Z.P., Carder, K.L., Mobley, C.D., Steward, R.G., Patch, J.S., 1998. Hyperspectral remote sensing for shallow waters, vol. 1. A semi-analytical model. Applied Optics 37 (27), 6329–6338.

Lee, Z.P., Carder, K.L., Mobley, C.D., Steward, R.G., Patch, J.S., 1999. Hyperspectral remote sensing for shallow waters, vol. 2. Deriving bottom depths and water properties by optimization. Applied Optics 38 (18), 3831–3843.

Lindell, T., Pierson, D., Premazzi, G., Zilioli, E., 1999. Manual for monitoring european lakes using remote sensing techniques. Environment and quality of life series. European Commission, Environment Institute, JRC Ispra, Luxembourg.

McEwan, J., Gabric, A., Bell, P.R.F., 1998. Water quality and phytoplankton dynamics in Moreton Bay, South-eastern Queensland. II. Mathematical modelling. Marine & Freshwater Research 49, 227–239.

Malthus, T., Mumby, P., 2003. Remote sensing of the coastal zone: an overview and priorities for future research. International Journal of Remote Sensing 24 (13), 2805–2815.

Mobley, C., 1994. Light and water: radiative transfer in natural waters. Academic Press, San Diego, California.

Mumby, P.J., Skirving, W., Strong, A.E., Hardy, J.T., LeDrew, E., Hochberg, E.J., Stumpf, R.P., David, L.T., 2004. Remote sensing of coral reefs and their physical environment. Marine Pollution Bulletin 48 (3–4), 219–228.

Phinn, S., Held, A., Stanford, M., Ticehurst, C., Simpson, C., 2002. Optimising state of environment monitoring at multiple scales using remotely sensed data. Proceedings of the 11th Australasian Remote Sensing and Photogrammetry Conference, Brisbane, Causal Publications.

Phinn, S., Dekker, A., Brando, V., Roelfsema, C., Scarth, P., 2004. MR2 - Remote Sensing for Moreton Bay. Brisbane, Report Prepared for CRC for Coastal Zone, Estuary and Waterways Management: Brisbane, 95 pp.

Phinn, S., Stow, D., Franklin, J., Mertes, L., Michaelsen, J., 2003. Remotely sensed data for ecosystem analyses: combining hierarchy and scene models. Environmental Management 31 (3), 429–441.

Rice, J., 2003. Environmental health indicators. Ocean and Coastal Management 46, 235–239.

Roelfsema, C., Phinn, S., Dennison, W., Dekker, A., Brando, V., 2001. Mapping *Lyngbya majuscula* blooms in Moreton Bay. In: Proceedings of the International Geosciences and Remote Sensing Symposium 2001, Sydney, CD-ROM Proceedings, IEEE-Piscataway, NY, USA.

Tibbets, I., Hall, N., Dennison, W.C., 1998. Moreton bay and catchment. School of Marine Science, the University of Queensland.

Trinder, J.C., Milne, A.K., 2003. Determining sustainability indicators by remote sensing. ISPRS-Highlights 8 (2), 23–25.